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High-T_c SNS Junctions: A New Generation of Proximity-Coupled Josephson Devices

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The subjects of mesoscopic Josephson junctions and the proximity effect are intimately related. This paper reviews this evolution of proximity-coupled Josephson junctions from the early investigations on low temperature superconductor-normal-superconductor junctions through the introduction of hybrid superconductor-semiconductor devices and the resulting interest in mesoscopic Josephson junctions, to the recent development of high temperature devices.

§ 1. Introduction

In the first generation of proximity-coupled devices, ordinary normal metals were used to weakly couple low temperature superconductor (LTS) electrodes to form superconductor-normal-superconductor (SNS) Josephson junctions. This allowed conventional proximity effect theory[1)] to be thoroughly tested and verified. In the succeeding generation, semiconductors were substituted for the normal metals. The extension of proximity effect concepts to low carrier density systems resulted in both experimental and theoretical work in several new areas. These included, for example, superconductivity in two dimensional electron gases in regimes of ballistic transport and mesoscopic phenomena. It also forced serious consideration of the electrical properties of superconductor-semiconductor (SSm) contacts. These developments are important in investigating the behavior of high temperature superconductor (HTS) SNS devices, the third generation of proximity-coupled Josephson junctions.

This paper discusses the history of proximity-coupled Josephson junctions with an emphasis on the relationship of the first two generations of devices to HTS junctions. Section 2 provides a historical overview of studies of proximity-coupled Josephson junctions with an emphasis on contacts. Conventional proximity effect theory is briefly reviewed in Section 3. The application of the theory to LTS metal and semiconductor-coupled devices is covered in Sections 4 and 5, respectively. Section 6 is devoted to the maturing field of HTS devices. Finally, Section 7 presents overall conclusions.

current-voltage characteristics in former case (Fig. 2-2a) are equivalent to ideal voltage-current characteristics in the latter (Fig. 2-2 b).

Duality of this nature is familiar in other systems.[6] The nature of the duality evident in Fig. 2-2 was not studied until the late 1980's, when it motivated this author to systematically investigate SSm contacts.’) By that time, SSmS devices were generally recognized as having an SINIS structure (except in rare cases that Schottky barriers are absent). The bulk of the Sm layer and the interracial Schottky barriers (insulators) act as N and I, respectively. Devices displaying Josephson behavior, as in Fig. 2-2a, were associated with the SNS-like extreme in which the insulating barriers are either extremely transparent or absent altogether. In the first set of systematic experiments in this area, changes in the doping level at SSm interfaces resulted in changes in junction current-voltage characteristics. These were attributed to a crossover from Andreev to quasiparticle currents[8,9] as the SSm contacts changed from SN-like to SIN-like with decreasing interfacial doping, This thin-film demonstration verified and expanded upon the results of earlier SN point contact experiments.[10]

The aforementioned experiments dealt with a crossover from excess low-voltage conductance (and high voltage current) for high interface transparency to conductance and current deficits in the opposite limit of low interface transparency. This picture qualitatively resembles the initial problem of crossing over continuously from the behavior of Fig. 2-2a to that of Fig. 2-2b. However, the picture that emerged from the experiments was incomplete because it did not include phase coherence and, therefore, could not account for the Josephson currents in devices with high contact transparency. Such currents are clearly expected in the extreme SNS-like limit. In fact, complete, systematic experimental studies of the crossover between the two extremes illustrated in Fig. 2-2 are still lacking. However, a similar crossover predicted for highly-transparent tunnel junctions did include Josephson currents.[11,12] This theory has been tested in experiments on tunnel junctions,[13] which were interpreted using an

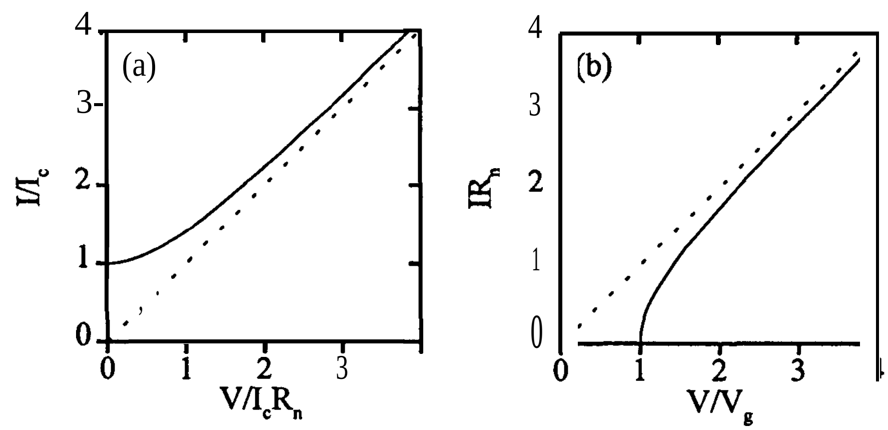

Fig. 2-2. Current-voltage characteristics at T = O for (a) an ideal Josephson junction, such as an SNS device, and (b) an SINIS junction (assumed to be equivalent to two SIN junctions placed back-to-back). Here I_c is critical current, R_n is normal state resistance, and $V_g = 2\Delta(0)/e$ IS the gap voltage.

already seen, a typical SSmS junction can be viewed as an SINIS junction in which I represents the interracial Schottky barriers.

In long ($L > \xi_n$) SNS, SINIS, and SSmS structures, the decay length of the order parameter in N is the coherence length, ξ_n. In most cases, pairs are destroyed by thermal fluctuations and ξ_n is essentially the distance a carrier travels in a time $\hbar$ /kT:

$$\xi_{nc} = \frac{\hbar v_n}{2\pi kT} \qquad (\ell >> \xi_n) \qquad (3 “1)$$

and

$$\xi_{nd} = \sqrt{\frac{\hbar D_n}{2\pi kT}} \qquad (\ell << \xi_n) \qquad (3 “2)$$

in the ballistic (clean) and diffusive (dirty) limits, where V_n, D_n, and ℓ are the Fermi velocity, carrier diffusion constant, and mean free path in N, respectively. The clean limit value is a good approximation if $\ell >> \xi_n$ or, equivalently, $\xi_{nc} << \xi_{nd}$. Similarly, the dirty limit value is a good approximation if $\ell << \xi_n$ or, equivalently, $\xi_{nd} << \xi_{nc}$. In general,[18] for arbitrary ℓ,

$$\xi_n \cong \sqrt{\frac{1}{\xi_{nc}^2} + \frac{1}{\xi_{nd}^2}} \qquad (3 “3)$$

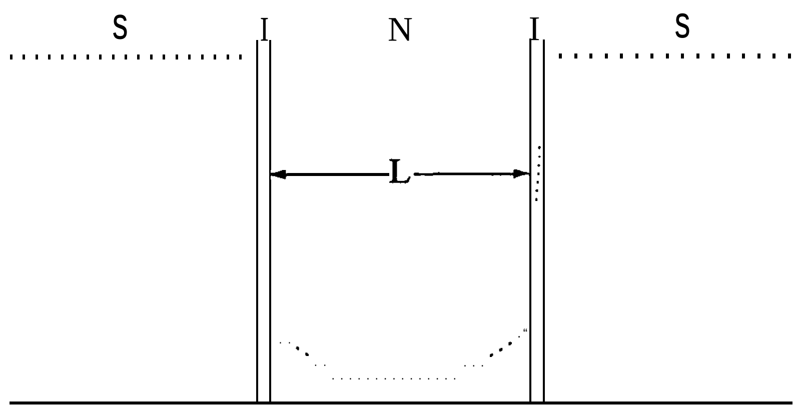

Fig. 3-1. Schematic diagram of the behavior of the superconducting order parameter (dotted line) in an SINIS junction. The interracial regions I, and the accompanying reduction in the order parameter, are absent in a pure SNS device.

evidence for the conventional proximity effect in a device. Conversely, failure to establish them provides strong evidence against such behavior.

3.5. *The Effect of SN Contacts*

These litmus tests apply to a wide variety of SNS, SINIS, and SSmS devices because the exponential decay that dominates proximity-coupled junction behavior is independent of the boundary conditions at the contacts. Contacts are nevertheless important, As seen from (3 ·4), I_c is related to the normal conductance, 1 /R_n, a parameter determined by both the bulk conductance of the N interlayer and the transparency of the SN contacts. The size of I_cR_n, a fundamental junction parameter important in circuit applications, is therefore determined by both the non-exponential boundary condition factor and the wavefunction decay, A reduction in the order parameter at the SN interface(s) reduces I_cR_n. For example, the presence of a potential barrier at the SN interfaces greatly reduces the order parameter in N. If $|T|^2$ is the transparency of the SN interfaces, critical (coherent) supercurrent, I_c, scales as $(|T|^2)^2$ because there are two SN interfaces involved. The normal conductance, $1/R_n$, scales as $|T|^2$ Therefore, I_cR_n scales as $|T|^2$. Typically $|T|^2 << 1$ and I_cR_n is reduced by orders of magnitude from its optimum value when interracial barriers are present.

§ 4. 1st Generation: LTS SNS Devices

Most research on the stationary properties of LTS SNS devices was conducted prior to existence of a complete microscopic theory of SNS junctions. Confirmation of the validity of conventional proximity effect theory for LTS devices depended on the litmus tests outlined above.[2)] The primary predicted feature, the exponential dependence of $I_c(T;L)$, is common in LTS SNS devices. The characteristic length in the exponent is indeed ξ_n, the expected normal coherence length obtained from the relevant N transport parameters. In some cases, overall quantitative agreement with (3· 4) has been observed.[18)]

There has been little early experimental work on the role of interface resistance in LTS SNS devices with metallic interlayers. Interface resistance in proximity effect structures was recognized early on as extremely detrimental,")

§ 5. 2nd Generation: SSmS Devices

5.1. *Litmus Tests*

In SSmS Josephson junctions, the Sm region contains free carriers. The carrier density is orders of magnitude lower than in ordinary metallic N layers. As a result, significant band bending occurs at the interfaces, giving rise a large mismatch in transport properties or, in most cases, insulating tunnel (Schottky) barriers. High carrier nobilities are possible in some cases, allowing the clean limit to apply over a wide temperature range, a situation that does not occur with

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the possibility of Josephson field effect transistors.[32] These devices had limited practical prospects, but recent advances in fabrication technology[33] have enabled a number of interesting physical investigations into superconductivity in two-dimensional electron gases, ballistic transport, the proximity effect in the clean limit, and mesoscopic effects.[33),34] As a result, the common practice of discussing supercurrent in SSmS devices in terms of either a conventional proximity effect model or an artificially separate coherent Andreev reflection model is rapidly disappearing. In retrospect, this is not surprising, given the common physical origin of these phenomena.[34]

§ 6. 3rd Generation: HTS Devices

6.1. *Overview*

Much has been written about HTS SNS devices and their interpretation in terms of conventional proximity effect theory.[18] In 1994, an explicit suggestion was made that strong similarity of the temperature dependence of the critical currents of most HTS Josephson devices in the literature strongly hinted at a common, non-proximity effect origin for their properties.[35] The first convincing demonstration of conventional proximity effect behavior in HTS Josephson junctions followed soon thereafter.[36]

It is important to note that conventional proximity effect theory has not been tested to any great extent on HTS materials, or even at temperatures exceeding roughly 10 K. On the other hand, despite possible evidence for an unconventional pairing mechanism and order parameter symmetry in high-T_c materials, there is no *a priori* reason to believe that conventional proximity theory should not be applicable to HTS SNS junctions. In a review and analysis of the field of HTS SNS junctions,[18] K.A. Delin and I presented detailed arguments for applying conventional theory. We provided a complete, unified discussion of the theory that emphasized the common physical origin of various theoretical works that are often treated as independent or unrelated, discussed numerous HTS experiments in the light of that theory, and identified significant problems with many earlier treatments. Here, I will summarize that detailed discussion, emphasizing the dangers inherent in the common practice of interpreting device data in terms of *intended* structures.[37]

In contrast to the situation with SSmS devices in recent years, both the development of HTS Josephson junction fabrication technology and the interest in the physics of their operation has been motivated largely by the quest for practical, especially commercial, applications of HTS electronics. SNS devices have emerged as the basis for most of this worldwide effort because they have proven to exhibit better device properties and to be more manufacturable (at least in the context of integrated circuits) than other device types. The implications of proximity effect theory and experiments for practical device and circuit development have been discussed elsewhere.[38]

I_c due to the large mismatch between cuprate electrodes and noble interlayers has been ignored.[18] Thus, none of the noble metal-based HTS SNS junctions reported to date pass the litmus tests for conventional proximity effect behavior.

The resistance of nominally-SNS HTS junctions, such as noble-metal-coupled devices, is typically much larger than the resistance attributable to the normal interlayer alone: $R_n >> \rho_n L/A$. Evidently, interface resistance, due to the presence of tunnel barriers at one or both SN interfaces, dominates, Typical SNS structures are therefore interpreted as actually being SINIS in nature.

Of course, the effect of interracial barriers is to drastically reduce I_cR_n. Yet, devices with relatively large I_cR_n products are reported. As in the SSmS case, it is sensible to postulate that the insulating interracial barriers are porous, resulting in an enhancement of the overall resistance roughly inversely proportional to the reduction in critical current (leaving I_cR_n approximately unaltered). This would leave the temperature and electrode separation dependence characteristic of proximity effect behavior unaltered and the litmus tests for conventional proximity effect theory would still apply. Specifically, a quasi-linear $I_c(T)$ dependence independent of electrode separation in a nominally SNS device cannot be accounted for by invoking inhomogeneous interfaces.

The failure to apply the standard tests in the case of noble-metal-coupled junctions, as well as in other types of nominally-SNS HTS devices, represents a significant reversal of the evolution of the first two generations of SNS devices and resulted in much confusion.[18]

6.3. *Oxide Interlayers*

The mismatch of properties between ordinary metals and oxide superconductors reduces the strength of the proximity effect between them.[18),44),45)] Structural and chemical incompatibilities preclude epitaxial layered device structures. An alternative approach is to use oxide normal metals as interlayers in epitaxial SNS junctions. Coherence lengths in oxides are small[18)] but interlayer thickness can be very small because it is controlled by the thickness of a deposited film. Initially, $PrBa_2Cu_3O_{7-y}$ was used as an interlayer in sandwich junctions.[46),47)] These devices were interpreted, at least early on, as SNS junctions, but the standard litmus tests were never applied.

High-T_c SNS junctions fabricated on edges (ramps) etched into $YBa_2Cu_3O_{7-x}$ were first fabricated with $PrBa_2Cu_3O_{7-y}$ interlayers.[48)] An SNS interpretation was supported for these devices by a roughly exponential dependence of $I_c(L)$.[49)] However, $I_c(T)$ exhibited the quasi-linear dependence characteristic of grain boundary junctions independent of L. 18) This is true of most of the large body of available experimental work on oxide-based SNS junctions.

Basic properties of $PrBa_2Cu_3O_{7-y}$ such as resistivity vary widely range depending on preparation conditions. Its behavior at low temperatures is usually not even metallic, precluding conventional proximity effect behavior. For this reason, recent discussions have focused on possible resonant tunneling transport in these devices.[50)] fabricated with both $YBa_2Cu_{2.79}Co_{0.21}O_{7-x}$ and $Y_{0.7}Ca_{0.3}Ba_2Cu_3O_{7-x}$ interlayers.[54),5 5),56)] These interlayers are superconductors ($T_{cn} \approx 50$ K), but the junctions are expected to act as SNS devices for $T > T_{cn}$.

Eqn. (3 · 4) is applicable in the case of an SNS junction in which N has a finite critical temperature, T_{cn}. Of course, the expression for ξ_n must be modified appropriately to diverge at $T_{,n}$, rather than at T = O. [(8)] This is illustrated in Figure 6-1. Note the significant enhancement of ξ_n over that in a non-superconductor and the fact that its true value is closer to the dirty limit than the clean one, both of which overestimate ξ_n. (The parameters used in this example are those of Ref. 36.)

The experimental data were analyzed using conventional proximity effect theory.[36)] I_c(-L) was calculated using the best available estimates of the relevant parameters, Excellent quantitative agreement between the calculated I,(T) curves and the experimental data was obtained in the case of $Y_{0.7}Ca_{0.3}Ba_2Cu_3O_{7-x}$ junctions with various values of L, It was argued that this agreement was the most convincing evidence to date for proximity effect behavior in cuprate SNS junctions and represented strong evidence that conventional proximity effect ideas are indeed applicable to high-T_c SNS junctions. For $YBa_2Cu_{2.79}Co_{0.21}O_{7-x}$ junctions, the calculated $I_c(T;L)$ was of the right order of magnitude and exhibited the expected qualitative features, but the $I_c(T)$ curves differed in shape with the

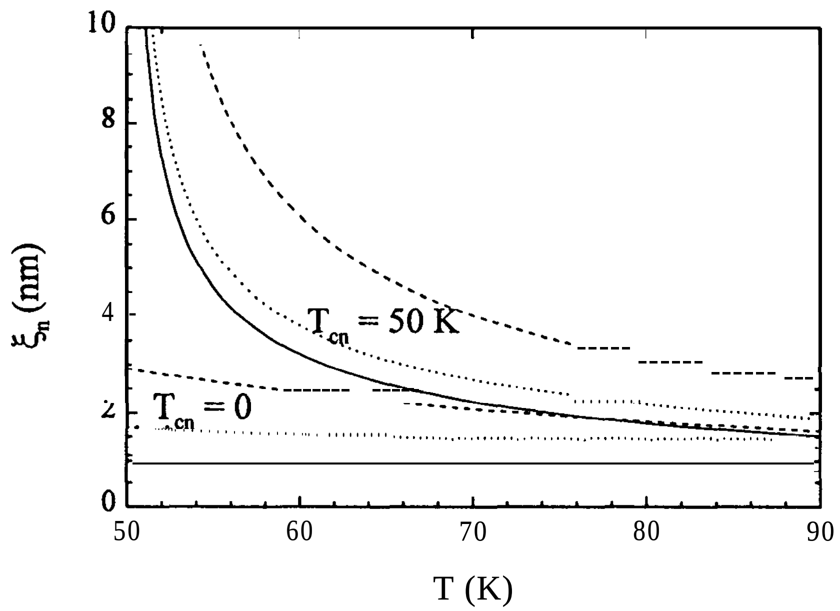

Fig. 6-1. Normal coherence length (solid curves) for an oxide interlayer with T_{cn} = 50 K (upper three curves). The case T_{cn} = O is shown (lower three curves) for comparison, illustrating of the enhancement of ξ_n even above T_{cn}. The dashed curves are clean limit values and the dotted curves are dirty limit values, both overestimates of the true coherence length (solid curves). In this example, the mean free path in N is 2 nm.

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6.5. *Summary*

The properties of superconductor-normal contacts in HTS junctions are clearly not well understood and remain a major issue, However, the larger issue in HTS SNS work has been the neglect of the behavior of the order parameter in N. Examples abound in the literature of individual HTS weak links exhibiting "SNS-like" behavior by virtue of their structures and current-voltage characteristics. Although these devices can have excellent electrical properties, there is significant reason to doubt that the vast majority of nominally SNS HTS junctions are SNS devices at all. Of course, this in itself does not directly impact their usefulness, However, if conventional proximity effect theory is to be used to guide device research towards a practical circuit technology, it is essential to apply the standard proximity effect litmus tests be applied and the suitability of a proximity effect interpretation verified.

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The tendency to ignore conventional theory maybe partly attributed to the lack of a comprehensive theory of the proximity effect in highly anisotropic, non-s-wave superconductors which are not themselves well-understood. However, basic ideas like overlapping wavefunctions, decay lengths obtainable from uncertainty principle arguments, and other presumably robust concepts from LTS experience, provide a reasonable starting point for examining experimental data.[18] In addition, there is evidence, in the form of edge junctions with doped cuprate interlayers, that conventional proximity effect ideas are indeed applicable to HTS devices and that they can continue to guide future device development.

Despite recent advances in understanding HTS SNS junctions, a number of outstanding questions of fundamental interest remain. The extent to which conventional proximity effect theory describes HTS SNS junctions is unclear. It is generally agreed that the order parameter in HTS materials does not exhibit the conventional s-wave symmetry, but the effect of order parameter on the proximity effect has not been adequately explored, Fundamental questions, such as whether or not a proximity effect can exist between a cuprate superconductor and an ordinary metal remain unanswered.

§ 7. Conclusions

HTS SNS Josephson junctions currently represent an outstanding problem in both conventional proximity effect theory and mesoscopic Josephson junction physics. Recent experience in developing a partial understanding of HTS junctions has also provided a valuable lesson in the importance of paying close attention to both past developments in related areas, in this case the first two generations of proximity effect devices, and far-reaching, fundamental theoretical ideas, in this case conventional proximity effect theory. These lessons may well prove to be equally valuable in the emerging field of mesoscopic Josephson junction physics.

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